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Chapter

Palm Oil Clinker as a Waste by-Product: Utilization and Circular Economy Potential

*Ahmad Hussaini Jagaba,
Shamsul Rahman Mohamed Kutty,
Gasim Hayder Ahmed Salih, Azmatullah Noor,
Mohammad Fakhuma Ubaidillah bin Md Hafiz,
Nura Shehu Aliyu Yaro, Anwar Ameen Hezam Saeed,
Ibrahim Mohammed Lawal, Abdullahi Haruna Birniwa
and Abdullahi Usman Kilaco*

Abstract

Conservation of natural resources to create ecological balance could be significantly improved by substituting them with waste by-products. Palm oil industry operations increases annually, thereby generating huge quantity of waste to be dumped into the landfill. Palm oil clinker (POC) is a solid waste by-product produced in one of the oil palm processing phases. This chapter is designed to highlight the generation, disposal problems, properties and composition of POC. The waste to resource potentials of POC would be greatly discussed in the chapter starting with the application of POC in conventional and geopolymer structural elements such as beams, slabs, columns made of either concrete, mortar or paste for coarse aggregates, sand and cement replacement. Aspects such as performance of POC in wastewater treatment processes, fine aggregate and cement replacement in asphaltic and bituminous mixtures during highway construction, a bio-filler in coatings for steel manufacturing processes and a catalyst during energy generation would also be discussed. Circular economy potentials, risk assessment and leaching behavior during POC utilization would be evaluated. The chapter also discusses the effectiveness of POC in soil stabilization and the effect of POC pretreatment for performance enhancement. Towards an efficient utilization, it is important to carry out technical and economic studies, as well as life cycle assessments, in order to compare all the POC areas of application described in the present review article. POC powder has proven to be pozzolanic with maximum values of 17, 53.7, 0.92, 3.87, 1.46, for CaO, SiO₂, SO₃, Fe₂O₃ and Al₂O₃. Therefore, the present chapter would inspire researchers to find research gaps that will aid the sustainable use of agro-industry wastes. The fundamental knowledge contained in the chapter could also serve as a wake-up call for researchers that will motivate them to explore the high potential of utilizing POC for greater environmental benefits associated with less cost when compared with conventional materials.

Keywords: Palm oil clinker, Waste utilization, Circular economy, Palm oil mill, Sustainable environment

1. Introduction

Oil palm, commercially named as *Elaeis guineensis*, is one of the main agricultural crops that thrives in a hot tropical climate. It produces vegetable oil fit for human consumption. As can be seen in **Figure 1a**, the tree is naturally brown and seed reddish in color because of a high betacarotene content. The oil palm industry has been conveniently quoted as the main sector producing abundant biomass as renewable sources in different forms; these include empty fruit bunches (EFB), mesocarp fiber (MF), palm shell (PS), oil palm fronds (OPF) and oil palm trunks (OPT). Palm oil industries face significant challenges in meeting the increasingly stringent environmental regulations on waste disposal.

Palm oil clinker (POC) is a waste by-product generated in one of the oil palm processing phases [1]. It is a residue from the heating zone of a steam boiler during electricity generation produced in huge amount from oil palm fibers and shells calcination in a suitable proportion of (30:70) at 100–850°C [2, 3]. It is subsequently cooled at air atmosphere [4].

Physically, POC shown in **Figure 1b** are naturally porous, flaky, gray in color, irregular in shape, lighter in weight, with rough and sharp broken surfaces [5, 6]. They are mostly presented as solid lightweight materials between the sizes of 2 and 15 cm [7]. POC is made up of inorganic oxides, 3.35% organic carbon and minerals like halite, lysite, eglestonite, elatossite, quartz and cristobalite [8]. Chemical oxides composition of POC highlighted in **Table 1** varies according to several factors. Some of these are: fiber to shell ratio, applied incineration process temperature, palm tree location soil condition, POC form (nano, powder, fine or coarse particle size) etc. [7, 9]. POC is a pozzolanic aggregate capable of producing appropriate attachment in a geopolymer matrix because of alumina-siliceous compounds presence [10]. It is no more news that, pore structure has a close association with the resistance of cement-based substances to fluid infiltration. These include, pore size distribution, interconnectivity and porosity [11].

Oil palm extraction rate has rapidly increased due to the increasing oil palm global demand [24]. As a consequence, fresh porous lumped POC is continuously

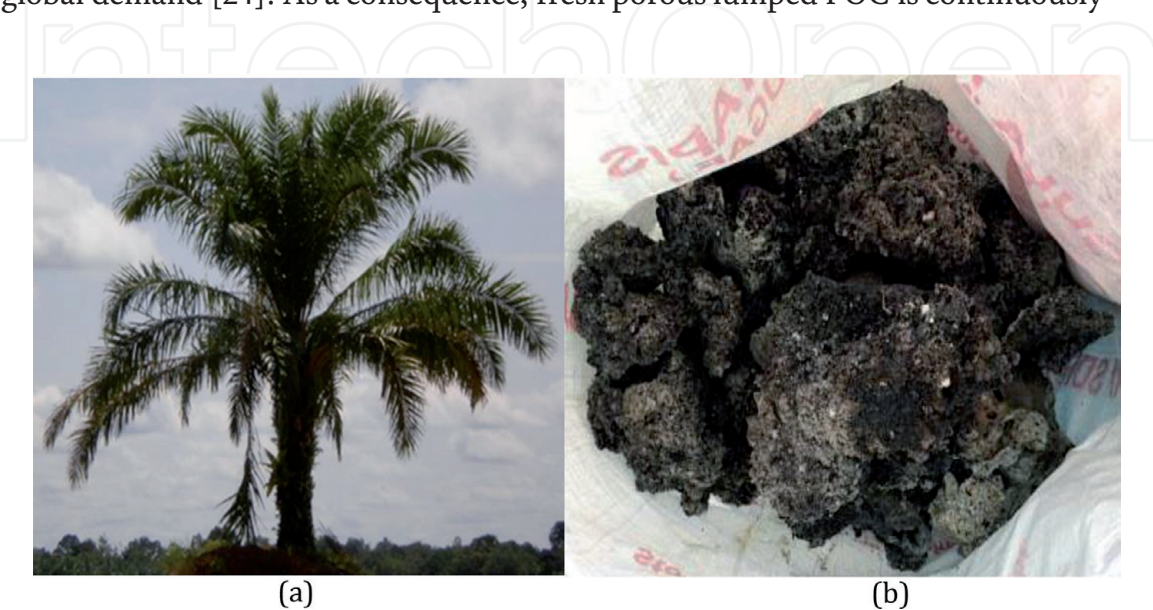


Figure 1.
(a) An oil palm tree and (b) palm oil clinker chunks.

State of POC	Chemical compositions												Ref.
	CaO	SiO ₂	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	MgO	P ₂ O ₅	K ₂ O	TiO ₂	Mn ₂ O ₃	Na ₂ O	Others	
Powder	6.37	59.90	0.39	6.93	3.89	3.30	3.47	15.10	0.29	—	—	0.36	[5]
Powder	3.20	61.29	0.10	4.31	5.89	3.16	3.12	10.79	0.12	—	—	—	[12]
Powder	3.26	60.29	0.11	4.71	5.83	3.76	3.10	7.79	0.13	—	—	—	[7]
Powder	3.28	60.29	0.31	4.71	5.83	4.20	—	—	—	—	—	—	[13]
Powder	6.93	63.90	0.21	3.30	3.89	3.37	2.12	10.20	—	—	—	—	[6]
Powder	3.89	65.30	0.09	5.65	4.23	3.72	0.78	13.65	0.13	—	—	—	[14]
Powder	8.00	60.00	—	4.00	4.00	5.00	5.00	12.00	—	—	—	2.00	[9]
Powder	3.28	60.29	0.31	4.71	5.83	4.20	3.78	7.24	0.10	0.12	0.20	—	[15]
Powder	6.37	59.90	2.60	6.93	5.37	3.13	0.07	15.10	0.12	0.12	0.24	—	[16]
Powder	4.82	63.10	0.15	9.00	3.20	3.50	3.09	12.50	0.21	0.12	0.16	0.13	[17]
Powder	6.09	42.30		3.288	3.09	2.41	2.95	15.20	0.17	—	—	—	[18]
Powder	7.05	55.39	0.19	10.81	2.18	2.00	3.97	17.7		—	—	0.28	[19]
Sand	6.37	59.90	0.39	6.93	3.89	3.30	3.47	15.10	0.29	—	—	0.36	[20]
Sand	5.74	65.40	0.64	2.71	1.95	6.40	6.56	9.52	0.11	0.17	0.32	—	[21]
Sand	3.28	60.29	0.31	4.71	5.83	4.20	3.78	7.24	0.10	0.12	0.20	—	[22]
Sand	17.00	53.7	0.92	3.87	1.46	2.37	5.29	13.9	—	—	—	—	[23]
Coarse	8.16	59.63	0.73	4.62	3.70	5.01	5.37	11.66	0.22	—	0.32	0.58	[2]

Table 1.
Chemical composition of POC.

generated [25]. The produced POC in the boiler is mixed in suspension, moved from the combustion boiler, and deposited in the factory yard [15]. It is a solid waste product of little to no economic benefit that causes pollution of the atmosphere, soil degradation and ground water contamination [8]. In recent times, it is mostly dumped in landfills that not only causes soil pollution but go as far as contaminating ground water [26]. It is important to note that the continuous dumping activity would cause waste accumulation at the dump site and creates the need to allocate new disposal area. Continuous disposal would result in waste rack up at the dumpsite, necessitating the allocation of new space for landfills. This would have negative consequences for the environment as fertile land is converted into a refuse collection area [27].

Besides overcoming waste disposal problems, integrating low cost and environmentally-friendly waste materials in new and sustainable product development would help in environmental pollution control, appropriate land use and promoting sustainability [16, 28]. Therefore, reusing POC for different applications would assist in natural resources preservation, reduce greenhouse gas emission, pave way for proper consumption and producing cleaner environment [11, 29].

With the technological advancement, there is a need for a change in using traditional old materials for industrial applications. Raw materials used by industries are affecting the environment to a larger extent. There is a dire need to change the current scenario especially for developing countries [23]. To achieve the concept of green technology, many attempts have been carried out to develop low-carbon footprint products or techniques. Due to their high mechanical properties and environmental benefit, POC appear as a future prospective industrial material and have applications in different areas. This article reviews the physical, chemical and microstructural properties of palm oil clinker (POC) by-products of palm oil. It aims to give a comprehensive survey of already-well-established or future potential energy applications of POC. A critical comparison of their use in different area is reported and their modification by various physical and chemical routes is detailed. The new direction beyond the state of the art is the application of POC in Nano form. This is why only one [1] article is found in this chapter.

2. Waste to resource potentials of POC

2.1 POC in geopolymer made structural elements

Geopolymer is an inorganic material that can be formed through the use of a binder. According to [30], any material that contain silica and alumina can be utilized as a binder. Alkali activators are also important for the production of geopolymers. Numerous high silica and alumina containing waste materials could be utilized for geopolymer production due to their pleasing size, shape and chemical composition. POC, considered a pozzolanic aggregate, has the capacity to create good bond in geopolymer matrix as it possesses the aforementioned characteristics. In contrast to POC with OPC concrete, the use of a geopolymer binder increases the workability and strength of POC concrete thus lowering its water absorbability. A green and long-lasting structural lightweight concrete can be produced by combining POC with Fly ash-based geopolymer binder [31]. Utilizing POC particles in the geo-polymeric specimen results in structural elements with good resistance to water absorption.

Sustainability in high strength concrete production can be achieved by combining POC with fly ash as a geopolymer based binder. Designing and mixing concrete with 100% POC aggregate can give rise to a concrete with compressive strength >30 MPa and a density of 1821 kg/m³. However, 32% strength reduction was experienced as natural aggregate was substituted by OPC. 75% POC aggregate

replacement in geopolymer concrete mixtures has been proven by [31] to be the most effective one. As POC concentration increases in geopolymer concrete mixtures, water absorption increases as density decreases.

POC sand was used for full sand replacement in a geopolymer mortar and achieved comparable mechanical properties showing high resistance to MgSO_4 and HCl solutions. 53 MPa was recorded as the 28-day compressive strength with 17% density reduction [32].

A geopolymer concrete that contain 100% POC as coarse aggregate was designed and evaluated. According to the results, 41.5 MPa was the highest compressive strength achieved at 28 days curing with a density range of 1910–2172 kg/m^3 . Splitting tensile strength increased and UPV values were also good. POC also improved the compressive toughness of the geopolymer mortar. The study concluded that, structural grade lightweight geopolymer concrete could be produced by using POC [10].

2.2 POC in conventional structural elements

The physical characteristics of POC used by several researchers are shown in Table 2.

2.2.1 POC as a coarse aggregate

The application of commercial aggregates was minimized due to high production costs emanating as a result of excessive raw materials and energy consumption. They also increase the dead weight of structures. Therefore, introducing POC, being a porous and lightweight material that contain high volume of solid waste materials are used to produce structural lightweight aggregate with potentials for high strength and good workability concrete. POC density is said to be less than that of normal aggregate [33]. Even though substituting normal weight coarse aggregate with POC wrecks the splitting tensile strength and modulus of elasticity, it however improves the concretes compressive strength [43].

The physical properties of POC aggregate have a notable influence on produced concrete properties. An equivalent of 1 m^3 of soil is saved when 1 m^3 of POC aggregates is utilized for concrete production instead of being discarded in a landfill. This would substantially lead to a safer and more productive climate [29]. CO_2 emissions were said to have decreased by 20% when natural aggregate was totally replaced with POC coarse aggregate [44]. POC aggregates are lightweight and porous by nature, and they contribute to the reduction in concrete structural density [1].

POC increases concrete mixtures porosity and permeability. Compressive strength reduction of about 65% was recorded at full POC replacement. Nonetheless, concretes with lower strength could be used for pedestrian trials and walkways construction [38].

POC aggregate crushing value is three times less than that of gravel aggregate, thereby indicating higher energy consumption [16]. Having a density of 1990.33 kg/m^3 , makes POC aggregates ideal for use in lightweight concrete mix proportions [40].

Experimental investigation was carried out on concrete substituted by POC as a filler and an aggregates material for high strength concrete (HSC) creation. The permeable nature and uneven form of POC coarse had a negative impact on the fresh concrete mix's workability. Nonetheless, adding POC powder as a filler improved the workability. Adding POC powder in POC concrete mixes improved compressive, splitting tensile and flexural strengths by 0–13%, 2–10% and 1–9%, respectively compared to POC mix without POC powder. According to Rapid Chloride Permeability Test (RCPT) carried out, both POC concrete mixes, with and without POC powder, have a strong resistance to chloride penetration with very low permeability category <100°C [7].

Size of aggregate (mm)	Bulk dry density (kg/m ³)	Saturated density (kg/m ³)	Specific gravity	Water absorption (%)	Aggregate impact value	Aggregate crushing value (%)	Fineness modulus	Moisture content (%)	Los Angeles abrasion (%)	Compressive strength (MPa) @ 28 days	Splitting tensile strength (MPa)	Flexural strength (MPa)	Ref.
—	2050	2076	—	—	—	—	—	—	—	57	—	—	[33]
5–14	823	—	1.62	4.43	—	18.04	—	—	26.21	>30	—	—	[31]
—	1471	65	—	3.91	—	—	5.88	—	—	57.8	3.79	—	[34]
4.75–10	732	—	1.81	4.35	—	56.44	—	0.28	—	55.2–83.5	—	4–7.8	[7]
5–14	781.08	1769.2	1.82	4.35	25.36	18.08	27.09	0.07	27.09	30.9	2.29	—	[35]
—	860	—	1.69	7	36.3	21.2	—	—	23.9	—	3.05–3.31	4.48–5.38	[36]
—	1419	1875–1995	1.9	4.23	26.01	18.04	4.99	—	27.08	50–60	3.2–4.6	—	[37]
—	782	—	1.8	3.56	—	—	6.32	—	—	61.67	—	—	[2]
4.75–14	732	—	1.73	3 ± 2	—	56.44	—	0.5	—	33.01–39.32	2.61–3.28	3.75–4.42	[5]
4.75–9.5	732	—	1.88	3 ± 2	—	56.44	—	—	—	3.43–9.52	—	—	[38]
5–14	732	—	1.73	3 ± 2	—	56.44	—	1 ± 0.5	—	33–49	—	—	[27]
5–12.5	781.08	—	1.82	4.35	25.36	—	—	—	27.09	46	—	—	[39]
—	817	—	1.92	—	—	—	2.6	1.3	38.7	—	—	—	[40]
—	568	—	1.75	5.67	27.31	—	—	0.08	25.05	—	—	—	[41]
—	793	—	1.76	4.67	48.6	47.9	—	—	—	—	—	—	[25]
—	—	—	—	—	—	—	—	—	—	27.51	—	2.54	[4]
< 4.75	811	—	2.15	5.75	—	—	—	0.11	—	—	—	—	[7]
< 5	1118.86	—	2.01	26.45	—	—	3.31	0.11	—	—	—	—	[35]
<5	811	—	2.15	10 ± 5	—	—	—	0.5 ± 0.25	—	—	—	—	[28]
—	918	—	1.98	—	—	—	2.3	1.27	—	—	—	—	[40]

Size of aggregate (mm)	Bulk dry density (kg/m ³)	Saturated density (kg/m ³)	Specific gravity	Water absorption (%)	Aggregate impact value	Aggregate crushing value (%)	Fineness modulus	Moisture content (%)	Los Angeles abrasion (%)	Compressive strength (MPa) @ 28 days	Splitting tensile strength (MPa)	Flexural strength (MPa)	Ref.
≤ 4.775	—	—	1.92	3.3 ± 1	—	—	3.52	1.5 ± 0.5	—	53	—	—	[32]
—	113	—	2.08	3.6	—	—	3.12	—	—	—	—	—	[42]
≤ 4.75	835.2	—	1.92	3.3 ± 1	—	—	3.52	1.5 ± 0.5	—	—	—	—	[22]
—	1085	—	1.94	9.77	—	—	2.6	0.27	—	—	—	—	[18]

Table 2.
Physical properties of POC.

POC concrete beams have been known to provide sufficient notice of impending failure by exhibiting traditional structural ductile behavior. At service loads, the crack width (0.24–0.3 mm) of POC concrete beam was found to be within the BS8110 overall permissible value for durability requirements [45].

In an oil palm shell (OPS) lightweight concrete, OPS aggregates were partly replaced with POC coarse aggregates from 0 to 50%. The slump value, density (2–4%), compressive strength and modulus of elasticity (18–24%) of the OPS concrete increases as POC coarse aggregate increases in the mix. More so, at 20–50% POC coarse aggregate addition, grade 35 OPS concrete was upgraded to grade 40. As a result, it's classified as a high-strength lightweight concrete [36]. In a related study, authors reported a positive impact on both workability, UPV and compressive strength. Highest compressive strength of ~63 MPa which is about 43% higher than the control mix was obtained for the OPS:POC mixture. This may be due to the efficient POC and mortar interlocking. With maximum obtainable stress between 0.00173–0.00401 > the normal weight concrete (NWC), the OPS:POC mixture could have better shrinkage crack resisting capacity. Furthermore, a 2.5 fold rise in elasticity modulus could remarkably control deflection [45].

POC aggregate could be used to develop high-strength lightweight concrete with a 28-day compressive strength of 50–60 MPa and an oven-dry density of 1875–1995 kg/m³. At full water curing and air-drying curing conditions, equivalent compressive strengths were recorded. This proves that, POC lightweight concrete is not too delicate to curing method. The study suggests the use of regular sand with a nominal grain size not more than 2 mm. This is to improve elastic modulus of the concrete [36]. Ultrasonic pulse value (UPV) tests value for POC concrete was good with a compressive strength and hardened density of 33–49 MPa and 2074–2358 kg/m³ at 28 days respectively. At 10% POC replacement for coarse aggregate, grade 40 concrete was obtained. However, increasing POC replacement ratio with coarse aggregate reduces the concrete workability. The advantage of applying POC as a lightweight aggregate is to decrease concrete structures dead load by up to 35% without much loss in structural strength. The decrease in dead load can save construction cost without compromising structural integrity. Therefore, applying lighter waste materials such as POC can greatly reduce concrete costs, due to its low cost of RM 0.020 per kg. This will go a long way in reducing the need for non-sustainable natural resources. For structural application, shear failure mode of POC concrete beams were found to be close to that of regular weight concrete beams, and as well in line with ASTM: C330 [28].

Despite the concrete's higher porosity, self-compacting lightweight concrete (SCLWC) had strong UPV values. Tensile splitting strength, compressive strength and flexural to compressive strength ratio also met the strength requirement for SCLWC [25]. Therefore, SCLWC is classified as a form of lightweight concrete with a high strength because 28-day compressive strength >40 N/mm². As an actively mobilized material, POC was also able to amplify the filling and passing ability of self-compacting concrete. The concrete showed less segregation resistance due to low POC coarse density. Although obtained density values were in an acceptable range, coarse aggregates replacement with POC in SCLWC reduced density in oven-dry and saturated surface-dry conditions by 16% and 18%, respectively.

Lightweight aggregate concretes made of POC with 12% less dead load compared to the conventional concrete mix showed an acceptable splitting tensile strengths and workability without any segregation or floating at an average water to cement ratio. Interestingly, even after 28 days of curing, POC concretes did not achieve their maximum strength [34]. Testing the efficiency of POC in concrete slabs, the mechanical interlock (m) and friction (k) between the steel and concrete were found to be 117.67 N/mm² and 0.0973 N/mm², respectively. It was also

discovered that horizontal shear-bond strength and structural behavior are satisfactory, nearly comparable to the conventional concrete slabs and could be used for composite slabs construction. Compared to conventional concrete slabs, POC concrete slab possess a reduction in weight of 18.3% [35]. Under absolute air, water, and 3 days water curing, the abrasion resistance and strength properties of concrete comprising POC coarse aggregate were investigated. The compressive strength of POC concrete cured in air and in water for 3 days displayed comparable conduct, with a maximum loss in strength of about 5% and an acceptable abrasion resistance. Interestingly, abrasion resistance was improved when cured in full water [44]. Air curing application in a tropical environment permit POC concrete to achieve the desired strength due to the surroundings high humidity. However, water curing is the most appropriate curing method for POC light aggregate concrete, because it contains enough water to ensure proper hydration and pozzolanic reactivity [41].

2.2.2 POC as a fine aggregate

Palm oil clinker (POC) has in recent times being used for partial replacement of fine aggregates in structural elements. This was possible due to the grading features and particle size distribution similitude between sand and POC fine aggregate [5]. The particle size distribution of POC ranging from 100 to 400 μm , indicates that they are suitable for use as fine aggregates. A study by [4] found the compressive and flexural strength of concrete to be increasing with the sand replacement with POC. The study further confirms that fine aggregate replacement with POC had no remarkable impact on compressive strength. However, it decreasing concrete workability [28].

Sand was totally replaced by POC in a mortar designed using the volume-based approach. At 28-day curing, 41 MPa was recorded as the compressive strength of the mortar. POCs aids the gain of early-stage strength development for up to 77%. With 4.09 km/s as the POC mortar velocity, well-compacted specimens were obtained. The poriferous structure and rough nature of POC aids in the formation of a stronger bond with cement paste. The price of the mortar could be reduced by 16% when POC is utilized [22]. When POC was partially replaced with sand from 0 to 40% by weight of sand to investigate its effect on fly ash cement sand brick engineering properties, it was found that up to 30% POC usage enhanced the brick strength due to the pozzolanic effect of the fine clinker. Calcium hydroxide and silicon dioxide were responsible for the pore refinement and higher brick strength development [27]. Replacing OPC with fine aggregate increased the mortar sorptivity, initial and final water absorption because of its high porosity. OPC replacement changes the cement mortar thermophysical properties. At 100% sand replacement, compressive strength development ((7th day)/(28th day)) was higher than samples containing lesser amounts of OPC. Under the same conditions, the specific heat capacity of mortar boosted by ~41%. Thermal conductivity and diffusivity lessened by 72% and 76% respectively. This shows that, OPC replaced mortar has the potential to lower heat transfer and energy consumption in buildings [46].

In a related study at 100% sand replacement, it was reported that POC fine has the potential to produce 86% and 78% compressive strength at 28 and 56 days curing respectively and providing almost 97% durability when compared to the conventional mix. POC fine durability showed a satisfactory outcome with good resistance against corrosion risk. POC fine is capable of lowering the carbon emissions of mortar by 50%. More so, POC fine can improve the engineering economic index and engineering environmental index by 11% and 95%, respectively. Life cycle impact assessment (LCIA) shows POC's potential to encourage a healthier and safer community with substantial reduction in ecotoxicity [20].

Incorporating POC sand in OPS concrete is beneficial to reduce its sensitivity to lack of curing. OPC was used as a replacement for sand at 0–50% in an oil palm shell (OPS) lightweight aggregate concrete. It was discovered that the replacement does not affect the drying shrinkage strain. High percentage of POC replacement increased the water absorption of the concrete. The concrete was proven to possess high splitting tensile strength [42]. In comparison with normal mining sand, POC fine aggregates have lower density and higher water absorption. Surprisingly, the slump value of concrete containing 25% POC fine showed good workability. The POC fine replaced concrete was classified as high strength because 69–76 MPa was obtained as compressive strength for 28-day curing. 12.5% POC fine replacement in concrete is said to be practical and cost effective [47].

2.2.3 POC powder

POC powder is obtainable by grinding dry POC for ~8 h in a controlled ball mill at 150 RPM. It has been confirmed by several authors through microstructure analysis that POCP particles are blackish in color, irregular in shape and contain small pores with fibrous materials present [6]. SiO_2 , Al_2O_3 , Fe_2O_3 , MgO and CaO are the major components found in POC powder with oxide composition >71.09%. This proves that the powder satisfies the chemical requirement of Class F fly ash [6]. POCP and cement generally have similar fineness. However, the suitability of using them in concrete relies on their pozzolanic activity [7]. Strength activity index result proved that POCP is a pozzolanic material [48]. To ensure that the required workability can be attained when used for partial replacement of cement in mortars, POCP being a pozzolanic material would require more water [49]. The crystallinity index of quartz in POC powder utilized by [6] was 0.97 indicating partial disorderliness of quartz and pozzolanic reactivity of the powder. The major component in POCP present in quartz and cristobalite phases at 2θ angle of 26.87° and 20.45° , respectively is SiO_2 [6]. A significant hump in XRD pattern from $10\text{--}35^\circ\text{C}$ demonstrates the presence of an amorphous fraction that is reactive due to pozzolanic activity [48, 49].

The addition of POC powder to replace cement and quarry dust has greatly increased the fresh and hardened density and compressive strength of produced blocks. Classified as thermally efficient and light weight blocks, the properties of the produced blocks meet the required thresholds and were higher than those of the common stabilized compressed earth blocks [18]. The use of POCP for cement replacement of about 40% in a cement-lime masonry mortar is recommended based on fresh density, consistency and air content requirements. Split tensile strength at 90 days of curing was greatly improved due to pozzolanic reactivity of POCP at longer duration. Flexural bond strength of the POCP mortar attained about 70% of control mortar. It also reduced 32% carbon footprint, 20% cost saving and save reasonable amount of energy [15].

A study attempts to investigate the durability performance and microstructure behavior of masonry mortars where POCP was used for cement replacement. With a compressive strength of 12.5 MPa, 40% cement replacement appeared to be a reliable mortar in terms of durability front with similar 28-day drying shrinkage to control mortar mix. The mixture possess extremely good electrical resistivity [49].

POC powder significantly enhances concrete compactness. At 15% increment, it improves the modulus of elasticity for up to 60% as compared to normal concrete. This could be attributed to concrete stiffness enhancement. At same increment, highest splitting tensile and flexural strengths in the range of normal weight concrete were recorded. Also, 15% and 30% strength enhancements were obtained for flexural and compressive strengths (65 MPa). The study also found that utilizing

POC powder of ~15–20% as a filler or cementitious materials in producing 45 grade lightweight concrete, CO₂ was reduced [9]. In a similar study trying to improve concrete strength, authors used varying proportions of nano-palm oil clinker powder (NPOCP) for cement replacement. It was discovered that, as NPOCP content is increased in the concrete mix, density decreases. This is because, cement has higher specific gravity than NPOCP. However, increase of NPOCP content increases concrete workability. The highest and lowest compressive values were obtained at 10% and 40% NPOCP replacement levels [18].

POCP replacement level of up to 30% enhanced the resistance of recycled aggregate-based concrete against water absorption and risk of corrosion decreased to a “moderate” level after 90 days curing period. In terms of compressive strength, POCP optimal replacement level to attain satisfactory result is 20% in comparison with the normal mix [11].

In a study by [5], the surface voids of POC coarse were filled and coated with POCP as a filler material. This mixture could decrease the quantity of aggregates derived from primary sources that are continuously exploited. It also increases the paste content necessary to make the mixes more cohesive. A notable increment in flexural strength was attained between 5 and 25% higher as compared to the POC concrete with 20–30% attained for compressive strength. However, supplementing POCP led to a decrease in water absorption value by decreasing the pore size, thereby producing highly densified paste. Specimens that contain POCP were reported to exhibit greater chloride-ion resistance.

POC powder can reduce the cost of mortar by 41%, save 3.3% of cement production, 52% carbon emission reduction. 50% POC powder replaced mortar could achieve 70% strength and 60% structural efficiency as compared to normal mortar [16]. The pozzolanic reactivity, microstructure properties investigation and strength activity index result confirmed that POC powder has pozzolanic property and good for utilization in cement-based applications.

2.3 POC in wastewater treatment

Domestic and industrial activities discharge wastewater containing high concentrations of various contaminants into water bodies [50]. Wastewater usually full of contaminants is considered as any water that is not safe for the intended use. Wastewater as a hazardous substance/material is a by-product resulting from human activities [51]. However, it is a source of chemical and thermal energy. Industrial operations in different mining fields, battery manufacturing, tannery, smelting, electroplating, textile, leather, petroleum processes, etc. are described as the major sources of wastewater. Surface runoff, sewer infiltration and poor management of urban solid waste also generate wastewater. Discharging all these without treatment into watercourses exhausts the good quality of freshwater water bodies. Wastewater is known to contain toxic pollutants like heavy metals, organic substances (dyes, PAHs etc.) posing a great environmental threat for all living organisms [52, 53]. Therefore, reduction in effluent quantity and improving the quality would have major positive effects on land use and human health [51]. To achieve that, compliance with acceptable limits is required prior to discharging effluents into the environment. Researchers have engaged in developing safe, functional, cost-effective, and appropriate wastewater treatment technologies to improve the ecosystem, lessen pollutants' detrimental effects, and minimize the risk of global warming and climate change. Unfortunately, some technologies and materials have shortcomings. As a result, it is imperative to develop safe, cost-effective, and long-lasting wastewater treatment materials.

POC as a waste material have recently been utilized by several researchers for wastewater treatment using techniques such as adsorption, biological system etc. Arsenic adsorption with palm oil clinker sand (POCS) was studied by [54]. They found out that pH, arsenic concentration, POCS (mg), and temperature are the four significant variables that control arsenic adsorption. Similar to several other adsorbents, solution initial pH portrays the most prominent influence on adsorption. Water absorption, fitness modulus and specific gravity were said to be the POC properties responsible for arsenic adsorption and process stability. Furthermore, the rich microporous structure and surface functional groups POCs play a vital role in the marvelous arsenic adsorption.

In a conventional activated sludge system, POC acted as a submerged attached growth media for the treatment of domestic wastewater. Performance efficiency of the POC in the extended aeration system (EAS) was evaluated by COD, TSS, MLSS, and MLVSS. Comparing the performance of POC submerged system to a biological activated sludge system, it could be concluded that using POC as an attached growth system can reduce the organic contaminant in effluent discharge [55].

POC as a filter media in a sequence batch reactor system is capable of extending its useful life, and reduce the demand for manufacturing new and sustainable media. In a comparative analysis between two SBR reactors with and without POC as a submerged fixed media, the former has higher ammonia removal efficiency of about 90% while the latter has 85% [56]. In a related study treating domestic wastewater in an SBR system, the average removal rate for ammonia and COD were 0.001 mg ammonia/mg MLVSS and 0.0069 mg COD/mg MLVSS respectively. This amount to ammonia and 90% and 70% removal efficiencies for ammonia and COD respectively [57].

2.4 Soil stabilization

Deep foundations specifically for soft soil has been a problem for long time. This pushed geotechnical engineers to opt for Lightweight Concrete Pile (LCP) due to their peculiar properties such as low density, surface roughness, low strength and high porosity. Different materials have been utilized to improve the concrete pile properties for performance enhancement. POC incorporated concrete pile (p-LCP), foamed concrete pile (f-LCP) and normal concrete pile (NCP) for floating foundation were investigated by conducting static and dynamic load tests. Findings revealed that, higher compressive stress and driving resistance values were obtained for p-LCP and f-LCP when compared with NCP. Correlating the compressive stress and driving resistance values of p-LCP and f-LCP with the pile ultimate load carrying capacity, the applied load for p-LCP and f-LCP can be increased by 4.5% and 27.3% respectively. The driving resistance could also be increased by 27.6% and 16.5% for p-LCP and f-LCP, respectively. Therefore, the study concluded that, p-LCP or f-LCP are better than NCP for deep foundation of particular structure in soft soil [58].

2.5 Highway construction

In the underdeveloped, developing and developed nations, highway construction is vital for the well-being of citizens. This results to the over utilization of natural resources for the construction. However, most of these resources have different environmental and financial implications to the immediate community. Therefore, few researchers come up with the idea of using POC waste material for highway pavement construction application and help solve POC disposal issues.

A study assessed the effect of using palm oil clinker (POC) as a substitute to fine aggregate on the mechanical properties of stone mastic asphalt (SMA) mixtures. The results proved the suitability of 100% POC replacement for fine aggregate in SMA mixture, as it enhanced the drain down, resistance to moisture damage, resistance to rutting, and resilient modulus when compared to that of control mixture. However, 40% and 60% replacement are considered as the optimum because of their outstanding mechanical properties. It also possesses higher indirect tensile strength for wet and dry conditions. Cantabro loss (durability performance) for POC- 80 and POC-100 exceeded that of the control sample as all mixtures fulfilled the standard requirement of the maximum value (20%) for weight loss. Authors concluded that, the use of POC as fine aggregates can greatly improve asphalt mix performance in flexible pavement construction [21]. In a related study by same authors, using the Marshall mix design, to select the optimum binder content, asphalt mixture samples with different percentages of asphalt binder content (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%) were prepared. The results showed that POC could satisfy the mix design requirements in terms of Marshall stability, flow, quotient, and volumetric properties. However, POC has less effect on optimum binder content. The length of the elastic stage POC replaced mixture is higher than that of the control mixture, thereby, enhancing the elastic properties and making them more inclined towards plastic fracture. The fracture life of asphalt mixtures increases by increasing the POC content in the mix. As a result, the asphalt mixtures are strong and stiff enough to withstand permanent deformation following traffic loads [59].

A study undertaken by [23] employed a high shear mixer to determine the appropriateness of utilizing palm oil clinker fine (POCF) as bitumen modifiers by material characterization tests. The impact of modification mixing parameters was also evaluated. The result from characterization confirmed its pozzolanic property. Thus, suggesting the feasibility of utilizing it as a bitumen modifier. The optimum mixing parameters obtained were 900 rpm at 160°C for 30 min with 6.3% of POCF as the optimum dosage. The study gathered that the incorporation of POCF enhances conventional bitumen properties.

2.6 POC as a catalyst

In the downstream petrochemical industries, ethylene (C_2H_4) is one of the most highly sought raw materials. C_2H_4 is a primary precursor for surfactant fabrication, plastic manufacturing and polyethylene production. Rather than landfilling POC, the current work attempted the valorization of silica-rich POC into POC derived SBA- 15 (POC-SBA-15) catalysts and modulation of its surface acidity for C_2H_4 production via ethanol dehydration. 400°C temperature, 50 wt% ethanol concentration, 16 mL/g.h LHSV were found to be the optimal conditions for ethanol dehydration over POC-SBA-15 [5] with the lowest strong and highest weak acidity. The POC mix catalyzes the process for up to 105 h [26].

2.7 POC as a bio-filler

To improve the mechanical strength, water resistance and fire protection performance of steel structures, it is essential to use appropriate and cost-effective materials as bio-fillers in solvent-borne intumescent coatings. To that effect, waste by-products like chicken eggshells (CES), rice husk and POC are being used to lessen the use of synthetic fillers. To produce intumescent coatings, POC and hybrid fillers are homogeneously mixed with an acrylic binder and subsequently blended with flame-retardant additives. POC have the advantages of large volume availability and direct usage without further processing.

Study by [3] revealed that, the optimum composition of POC and hybrid fillers results in intumescent coating with the greatest fire retardancy with the lowest equilibrium temperature (171.3°C) because of its high thermal stability, high water resistance and excellent adhesion strength/mechanical properties. POC as a fire-retardant filler let the binder to mix appropriately, resulting in a more homogeneous coating with better interfacial bonding. It was discovered that combining POC with $\text{Mg}(\text{OH})_2$ fillers also enhances the adhesion strength of intumescent coating.

In a related study by same authors, hybrid fillers with POC were mixed in appropriate quantity of additives and acrylic binder to produce intumescent coatings. Findings revealed that, specimen with POC as a sole filler greatly enhanced the fire protection efficiency of the intumescent coating, with <10% temperature difference when compared to specimen with hybrid fillers. For hybrid fillers composition, specimen consisting of $\text{POC}/\text{Al}(\text{OH})_3/\text{TiO}_2$ greatly improved the coatings water resistance due to $\text{Al}(\text{OH})_3$ low solubility in water, while specimen containing $\text{Mg}(\text{OH})_2$ had higher mechanical strength because of the strong bond that exist between the acrylic binder/ $\text{Mg}(\text{OH})_2$ filler and metal surface [60].

2.8 Risk assessment and leaching in POC utilization

Heavy metal leaching from waste depends on the matrix's bonding energy and perhaps even the leaching state. In terms of POC, the concentration of heavy metals present depends on the palm oil mill boiler burning condition and geological condition of the location where palm oil tree grew [8]. POC solubility relies on different bonding energy in solid matrix. If the hydration energy exceeds existing bonding strength of POC matrix, POC dissolves into the solution; otherwise, the metals of POC are deposited as residue at the bottom of the vessel. Under normal environmental condition, heavy metals do not leach from solid matrix of POC, because the leaching values of heavy metals are well below the standard limit of risk. With POC acid soluble fraction in the range of 0.0–9.27%, risk assessment code (RAC) analysis by [8] confirms the safe incorporation of POC in cement-based applications because RAC values are <1%. Therefore, there is no potential threat to environment and health safety [8].

It's crucial to understand human exposure to ionizing radiation because radiation from natural sources can cause cancer and genetic mutations that influence future generations. Knowing the radiological health hazards caused by the incorporation of POC in building elements is very important. The radioactivity levels were measured by [12] and the activity concentration in POC was found to be less than 50 Bq kg⁻¹ world average values for building materials. To evaluate the potential radiological hazards, radiological parameters and hazard indices, such as absorbed dose rate, radium equivalent activity, and annual effective dose were determined. Obtained results were within the recommended standard limit, precisely less than unity. This implies that POC is safe to be used in concrete construction.

3. Pretreatment of POC for performance enhancement

3.1 Effect of hydrochloric (HCl) acid and magnesium sulfate (MgSO_4) attack

The effect of hydrochloric acid and magnesium sulfate attack on POC supplemented concrete was evaluated by [13]. The outcome proved that 30% POC addition minimizes concrete deterioration and loss in compressive strength when dipped in a HCl solution and a 30 MPa strength 90 days curing. The concrete

containing POC showed higher performance against deterioration, mass and strength loss. This could be due to low quantity of calcium hydroxide, well known as weak in acid attack resistance. However, when the concrete got exposed to MgSO_4 attack, less micro-cracks were seen.

3.2 Effect of thermal and chemical treatment on POC structural elements

Fire resistance of any structural element greatly depends on the stability of concrete ingredients at elevated temperatures. Therefore, researchers usually conduct thermal activation to evaluate its effect on physical and mechanical properties, crystalline structure, minerals, organic carbon content, morphology and chemical composition. Investigating these properties is necessary as they directly or indirectly affect the structural elements compressive strength. This was why Karim et al. [14] studied the effect of temperature on microstructure change and compressive strength of cement paste incorporated with POC. It was reported that, thermal activation at 600°C , and 800°C for a duration of 3 h yield higher residual compressive strength for POC specimen than that obtained for OPC specimen. This could mainly be due to the pozzolanic reaction of POC specimen when heated at elevated temperature. Also, C-S-H gels were more stable in POC containing cement paste after an elevated temperature exposure. This signifies that POC incorporated specimen has higher fire resistance. Crack formation was also higher in OPC paste surface, which is an indication of higher superiority of POCP in making fire resistant concrete.

In a related study by same authors [61], it was gathered that 580°C for 3 h is proven to be the appropriate condition for thermal activation effect on POCP as the compressive strength of mortar was significantly increased, organic carbon content in POC reduced as inorganic oxides content increases, with an increment rate of 3.4%, 3.5% and 3.4% for SiO_2 , Al_2O_3 and Fe_2O_3 respectively at $^\circ\text{C}$. Porosity reduced as fibers were eliminated and POC color transformed from black to gray. It was also discovered that thermal activation has no significant influence on POC crystalline structure. Therefore, it has been proven that thermal treatment can enhance POC pozzolanic reactivity by elevating the maturing process of hardened specimens and unburned carbon removal.

In concrete specimen prepared with 25%, 50%, 75% and 100% replacement of Oil Palm Shell (OPS) with POC as coarse aggregate at an elevated temperature up to 500°C for 30–60 min, POC aggregate experienced negligible weight loss of <1% with excellent resistance. As the POC content is being increased, number of cracks and crack width decreases. At 100% OPS replacement with POC, the loss of residual compressive strength of only 9% indicates the vast improvement of OPS concrete using POC [2].

In other to investigate the pozzolanic reactivity of POC powder by chemical pretreatment, the powder was replaced at 2.5–15.0% by weight of cement for pre-treated and untreated POC powder in mortar mixtures. POC impregnation with low HCl acid concentration was able to enhance its pozzolanic reactivity through the hike of active silica proportion and reduced impurities and traces of metallic elements. The combination of 0.1 M of HCl acid and 1 h of impregnation time was selected as the optimum pre-treatment parameters. The strength activity index of up to 7.5% of cement content replacement with pre-treated POC increased in the hardened mortar. Authors also concluded that, the pre-treatment process would enhance the pozzolanic reactivity of POC powder up to 170% higher, increase the proportion of amorphous silica up to 9.6%, and contribute more to the strength development of mortar compared to the untreated POC powder [19].

4. Circular economy

The circular economy seeks to sustainably merge economic activities with environmental protection. It stresses the utilization of solar, wind, biomass, and waste-derived energy in the product lifecycle. It also encourages material, product, and components re-use, repair, remanufacturing, upgrading, refurbishing, and cascading [62]. It is termed as a remedy for increasing positive environmental effects while increasing economic growth by incorporating alternative manufacturing, utilization, and disposal systems. It strives to step away from the ‘make, use, dispose’ approach and supports the cyclical application and utilization of processes. However complicates life for people because it requires consumers behavioral changes in terms of perception to values, patterns, and relationships [63]. The main foundation of circular economy is built on the foundations of structures that encourage the responsible and cyclical utilization of materials and energy to preserve the economic value of resources for as long as humanly possible. To accomplish sustainable development goals (SDGs), circular economy has been portrayed as an accelerator towards enhancing in areas of sustainability, resource management, social equality, social responsibility and productivity [64]. It not only stimulates economic development but also shifts demand from a linear “extract-produce-use-dump” model to a cyclical flow model. It is also said to reduce carbon footprint [65]. Interestingly, companies are now integrating the idea into their everyday operations.

4.1 Principles of a circular economy

Three principles of a circular economy have been described by the Ellen MacArthur Foundation, namely;

- By dematerializing and virtualizing service delivery, as well as promoting green technology and processes, a limited stock of natural resources will be conserved and optimized.
- Recycling, refurbishment, and remanufacturing of goods and services to regenerate and recirculate capital without lowering their value.
- Priorities for industrial prosperity are; damage reduction, waste elimination, and the use of sustainable and resilient resources [64].

4.2 Approaches to foster circular economy

The following have been identified as approaches for nurturing circular economy:

- Regeneration: ecosystem renewal and repair
- Sharing: asset reusing, updating, and sharing.
- Optimization: improved efficiency, remote sensing and control, waste elimination, and big data utilization.
- Loop: organic waste is processed, remanufactured, and biochemically extracted, resulting in outputs used as inputs in the economy.

- Virtualization: dematerialization by using digital and virtual services
- Exchange: implementing innovative service and business models, as well as new technical innovations [65].

According to literature, there are a variety of business models for adopting the circular economy. They are circular economy and:

- Manufacturing
- Supply Chain Management
- Energy (energy transition, renewable energy, and biogas for electrification)
- Consumer
- Waste Management e.g. (agricultural and industrial waste) [64].

Relating circular economy to the oil palm industry, it has been reported by researchers that quantities of various dry palm oil biomass wastes can be obtained for 1 ton of crude palm oil produced from fresh fruit bunches (FFB). They could be: six tons of palm fronds, five tons of empty fruit bunches, one ton each of mesocarp fiber and palm trunks, 250 kg of Palm kernel cake, and 500 kg of palm kernel shell Palm oil mill effluent (POME) (100 tons) [24, 66, 67].

As a commodity, palm oil acting as a feed, energy, and chemical source has proven to be successful in creating a sustainable and healthy circular economy. The development of the new circular economy paradigm pave way for proper utilization of palm oil clinker. In light of the circular economy strategy, the use of POC for many industrial applications earlier discussed in this chapter is gratifying for the environment and community's well-being.

5. Conclusion

This chapter was designed to highlight the generation, disposal problems, properties and composition of POC. The waste to resource potentials of POC were greatly discussed starting with the application of POC in conventional and geo-polymer structural elements such as beams, slabs, columns made of either concrete, mortar or paste for coarse aggregates, sand and cement replacement. Aspects such as performance of POC in wastewater treatment processes, fine aggregate and cement replacement in asphaltic and bituminous mixtures during highway construction, a bio-filler in coatings for steel manufacturing processes and a catalyst during energy generation were also discussed. Circular economy potentials, risk assessment and leaching behavior during POC utilization would be evaluated. The chapter also discussed the effectiveness of POC in soil stabilization and the effect of POC pretreatment for performance enhancement. During the study, it was discovered that POC utilization for intumescent coating can contribute to environmental conservation and reduce production cost. 37% of waste materials from palm industry are used in the development of green concrete and with the global significant rise in vegetable oil production, it is projected to grow even further. This is anticipated to rise further with the global increase in vegetable oil demand. Thus, the incorporation of POC as an alternative raw material for concrete work, with or

without pre-treatment, will help to maintain the construction industry's long-term viability. POC has been shown to function in a variety of concretes, including self-compacting, natural, lightweight, pervious, and supplementary cementitious materials. The present chapter could be used for researchers' foundational awareness that will motivate them to explore the high potential of utilizing POC for greater environmental benefits associated with less cost when compared with conventional materials. Finally, this chapter suggest future researchers to investigate the feasibility of utilizing micro, ultrafine and nano POC powder for various applications that will promote environmental sustainability.

Acknowledgements

The authors would like to express their gratitude to Universiti Teknologi PETRONAS (UTP) for supporting the research under the Fundamental Research Grant Scheme (FRGS) grant (015MA0-092). The authors would like to acknowledge also the support from Universiti Tenaga Nasional (UNITEN) under BOLD Research Grant 2020. The authors are also thankful to technologists; Mr. Zaaba bin Mohammad, Mrs Norhayama binti Ramli and Mr. Meor Asniwan Bin Mew Ghazali from the Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Malaysia for their assistance.

Conflict of interest

The authors declare no conflict of interest.

Author details

Ahmad Hussaini Jagaba^{1,2*}, Shamsul Rahman Mohamed Kutty^{1,3},
Gasim Hayder Ahmed Salih^{4,5*}, Azmatullah Noor¹,
Mohammad Fakhuma Ubaidillah bin Md Hafiz¹, Nura Shehu Aliyu Yaro^{1,6},
Anwar Ameen Hezam Saeed⁷, Ibrahim Mohammed Lawal^{2,8},
Abdullahi Haruna Birniwa⁹ and Abdullahi Usman Kilaco¹⁰

1 Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia

2 Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria

3 Centre of Urban Resource Sustainability, Institute of Self-Sustainable Building, Universiti Teknologi PETRONAS, Seri Iskandar, Perak Darul Ridzuan, Malaysia

4 Institute of Energy Infrastructure (IEI), Universiti Tenaga Nasional (UNITEN), Kajang, Selangor Darul Ehsan, Malaysia

5 Department of Civil Engineering, Universiti Tenaga Nasional (UNITEN), Kajang, Selangor Darul Ehsan, Malaysia

6 Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria

7 Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia


8 Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK

9 Department of Chemistry, Sule Lamido University, Kafin-Hausa, Nigeria

10 Civil Engineering Department, University of Hafr Al-Batin, Hafr Al-Batin, Saudi Arabia

*Address all correspondence to: ahmad_19001511@utp.edu.my and gasim@uniten.edu.my

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